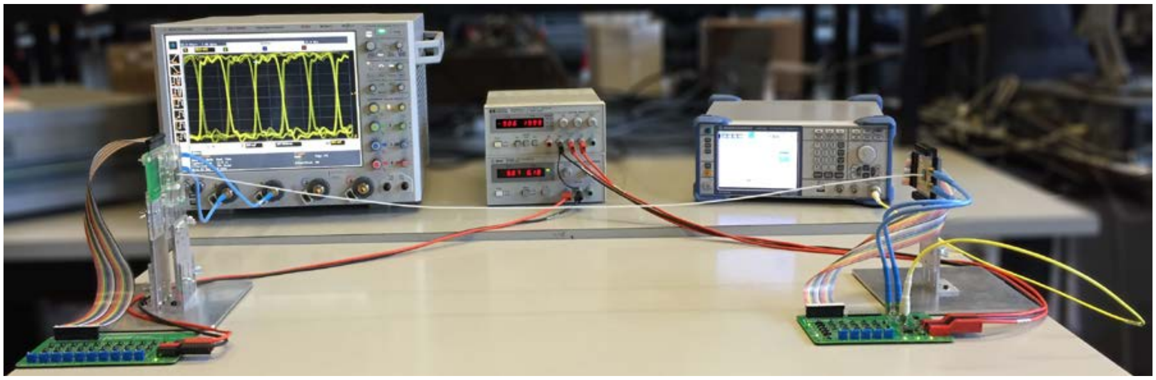

RF-through-Plastics: an alternative to copper and optical fiber

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Thanks to Moore's Law, standard CMOS technology enables circuits to operate in the millimeter-wave frequency range (30GHz - 300GHz). By making use of carrier frequencies in this frequency domain, wide-band communication systems benefit from the large bandwidth available. One of today's challenges is to transmit these millimeter-wave carriers over a distance of several meters to provide a Gbps communication link. Wireless communication suffers from the increased free space path-loss as shown in Figure 1. Plastic waveguides benefit from the low inherent transmission loss of polymers in the millimeter-wave frequency domain, what makes the plastic waveguide an ideal candidate for a low-loss, cost-friendly and light-weight directive channel.

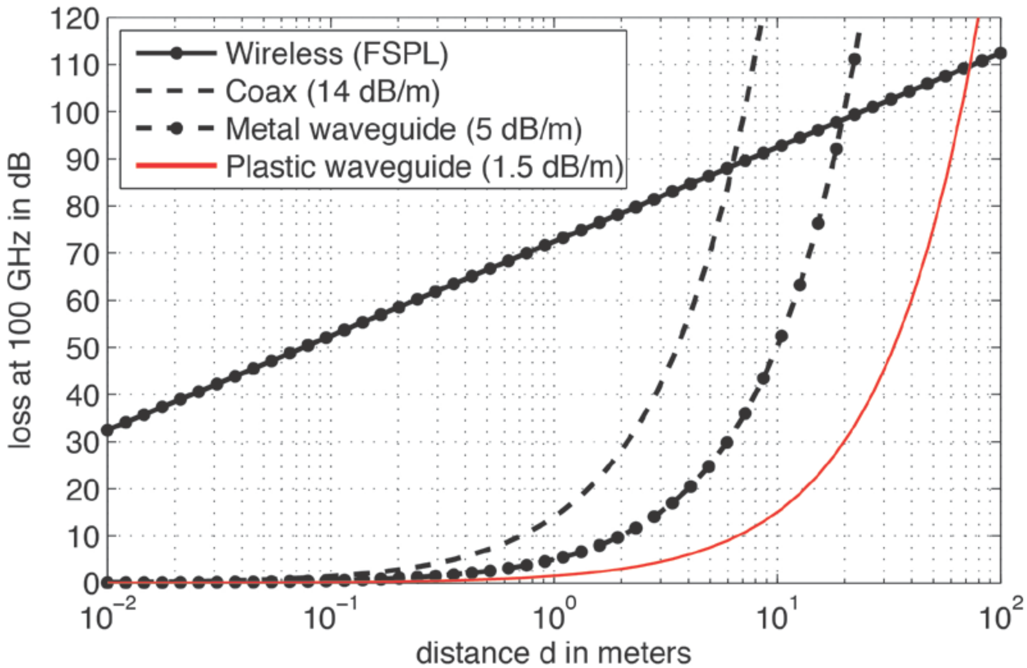

Figure 1. Loss of different millimeter wave channels: a wireless link, a coaxial cable, a metal waveguide and a plastic waveguide [rectangular polypropylene fiber with a cross section of 0.9x2.2mm^2] at a frequency of 100GHz.

Through the combination of millimeter-wave CMOS chips, small on-chip antennas and cheap thin plastic fibers, a novel communication concept for Gbps data transfer up to several meters was created that combines the benefits of copper wireline and optical interconnects. A Gbps link was demonstrated [1-3] with both transmitter and receiver chip in a 40nm CMOS technology and respectively a rectangular polypropylene rod and a hollow PTFE tube acting as the directive channel. These losses are acceptable for transmission lengths up to several meters. Figure 2 illustrates a simplified overview of the proposed solution.

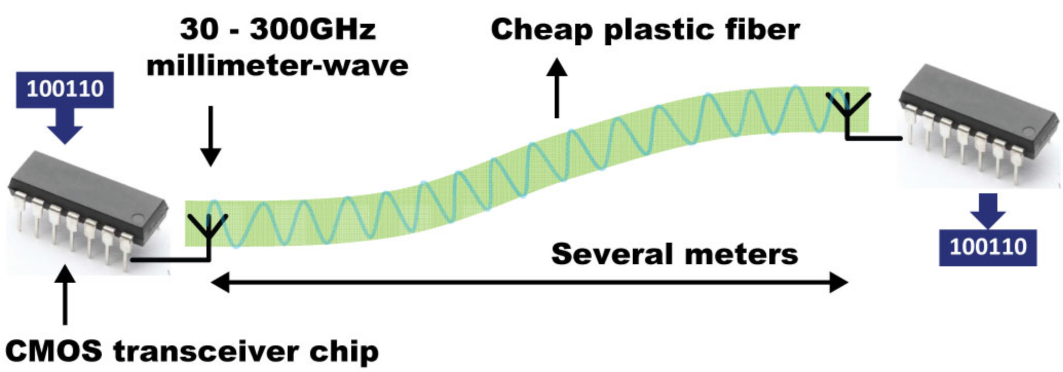

Figure 2. Simplified concept of the proposed millimeter-wave plastic waveguide link.

System implementation:

The communication concept is based on three low cost elements that are brought together:

1. **Low cost, light-weight and EMI-robust millimeter core plastic fiber with low transmission**

loss in combination with low dispersion in the frequency range from 30GHz to 300GHz.
Thin polymer fibers, made from standard very low cost plastic materials such as polyethylene, polypropylene, polystyrene, PTFE and many other polymers, are excellent dielectric waveguides. The diameter of these polymer fibers is in the range of one millimeter or smaller, corresponding to the wavelength to be transmitted. Our measurements indicate a loss of less than 2.5dB per meter for a commercial-grade hollow PTFE tube at a frequency of 120GHz, as shown in Figure 3a. These measurements are performed in the lab using a network analyzer with frequency extenders and horn antennas.

When the waveguide is bent, additional loss is introduced. With decreasing frequency, more power travels at the outside of the waveguide, so the wave is less tightly bound to the waveguide and the power is more easily lost in the bend. For a bend of 180 degrees with bending radius of 25mm, only 1.5dB of additional loss is measured as depicted in Figure 3b.

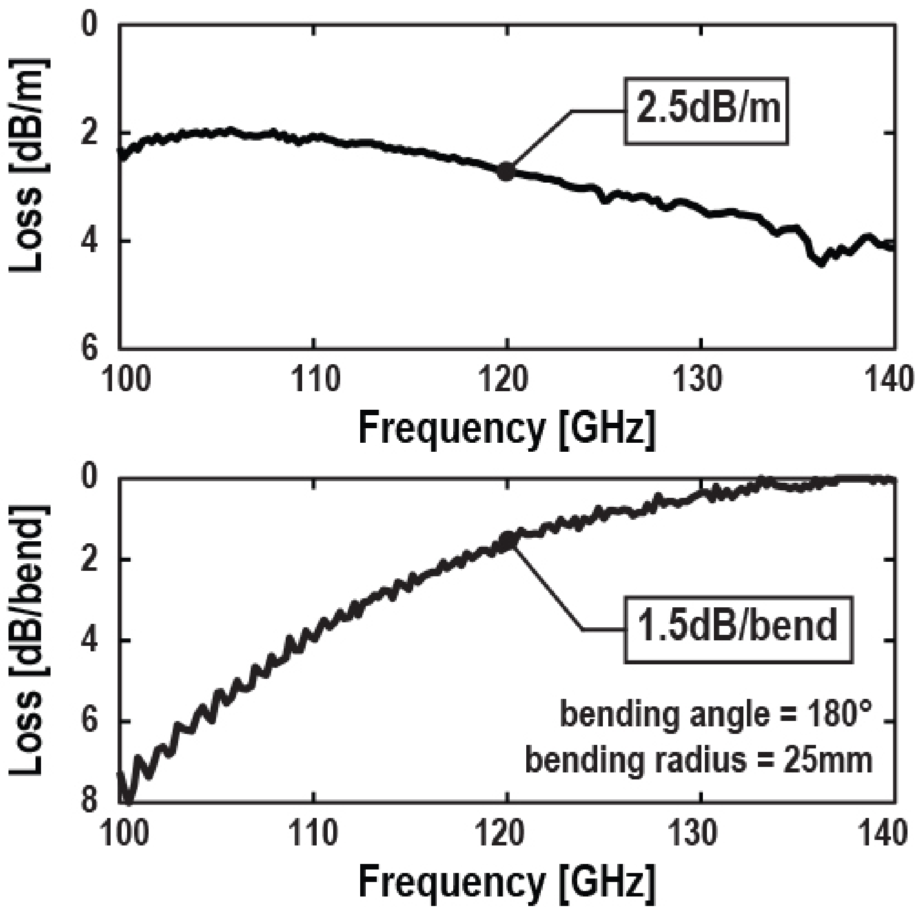

Figure 3. Measured (a) transmission loss [dB/m] and (b) measured bending loss [dB/bend] for a hollow PTFE tube with an inner and outer diameter of respectively 1 and 2mm.

Since wavelength and fiber diameter are in the same range, the number of modes for transmission through this fiber is very low, reducing or even fully eliminating modal dispersion. Dispersion is the main reason why optical communication over 1mm plastic optical fiber is not acceptable or even possible for in-car communication networks operating at 5Gbps and higher data rates.

Low transmission loss in combination with low dispersion enables transmission of data at high rates (>20Gbps) over medium distances (>20m) through the small, flexible and low-cost channel provided by the plastic material. These dielectric waveguides can be fabricated at very low cost.

2. **Low cost >10Gbps monolithic transmitters and receivers in standard CMOS silicon technology.** Thanks to Moore's Law, 40nm CMOS technology is available today as a standard technology. The fmax of 40nm MOS transistors is above 300GHz, making it possible for circuits to operate at sub-THz frequencies. These millimeter-wave transmitters, when using complex (QAM) modulation and coherent demodulation are able to transmit and receive data >20Gbps.

3. **Low cost antennas integrated in the package or PCB, or on the chip itself, without the need for electro-optical conversions.** The high operating frequency reduces the size of the antenna. As such, it becomes possible to integrate the antenna in the package or even on the chip [4]. This also results in a very easy and robust coupling between the chip and the plastic waveguide: the chip directly launches the electromagnetic wave into the plastic fiber without the need for EO/OE (Electrical-Optical) conversion. Elimination of electro-optical conversion is a significant cost improvement. Another advantage is the robustness against misalignment of the plastic waveguide relative to the antenna. The relaxed alignment requirements are a big advantage of the plastic waveguide because no accurate alignment of the connector is needed. It also makes this solution more robust against mechanical vibrations (e.g. automotive) and results in cheaper connectors (e.g. consumer electronics).

This combination of three low cost elements: Receivers and transmitters implemented in a single chip in standard silicon CMOS technology, on-chip integrated antennas and low cost plastic fibers constitute a breakthrough novel physical layer data communication in the tens of Gbps and distances up to several meters.

Markets:

The low cost implementation enables mass volume markets in consumer, industrial and automotive (e.g. infotainment) applications with a demand for high data rate communication links.

The amount of integration, using standard mass volume technologies, suggests that high quality and reliability levels can be reached relatively easily. The excellent coupling between transmitter and fiber and the full immunity of plastic fiber to electromagnetic disturbances, projects an excellent EMI performance.
Therefore, the predicted quality and reliability levels, as well as the projected EMI performance, enable safety critical automotive applications, such as needed for self-driving or driverless cars.

Research results:

To further investigate this concept, to better understand the design and implementation challenges and trade-offs, and to showcase that this idea can really work, the ESAT-MICAS laboratory of the University of Leuven is performing a research program, which includes the design, fabrication, characterization and demonstration of all four components of this new type communication system: single chip transmitters, single chip receivers, antennas and plastic waveguides. Table 1 gives a comparison with the state of the art plastic waveguide links.

In a first demonstrator [1] bits are transmitted through a plastic channel (polypropylene) of several meters lengths up to 9m. This lab demonstrator consists of a 90GHz (multilevel) ASK receiver chip in 40nm CMOS with on-chip bond-wire antenna, a rectangular plastic fiber with a cross-section of $2.2 \times 0.9 mm^2$ and a transmitter build with measurement equipment. We have measured the link for various data-rates (1 to 10Gbps) and distances (0.6m to 9m). The results have been presented at the European Solid-State Circuits

Conference in September 2013.

A second demonstrator [2] was developed in 2014 and contains both a transmitter and receiver chip in 40nm CMOS, working at an operating frequency of 120GHz. This demonstrator uses continuous-phase FSK modulation to reduce the power consumption and to improve the energy efficiency to 1.8 pJ/bit/m Figure-of-Merit. The increase in carrier frequency from 90GHz to120GHz reduces the dimensions of the plastic channel and the hollow fiber reduces the transmission loss.

	ISSCC '11 [5]	JSSC '11 [6]	MWCL '13 [7]	ESSCIRC '13 [1]	ISSCC '15 [2]
Technology	40nm CMOS	40 nm CMOS	65nm CMOS	40nm CMOS	40nm CMOS
Supply [V]	1.1	1.1	1	0.9	0.9
Carrier Frequency [GHz]	80	57	60	87	120
Material Dimensions	PS 1.1mm x 8mm	PS 1.1mm x 8mm	PTFE Ø 3.2mm x Ø 2.6mm	PP 0.9mm x 2.2mm	PTFE Ø 2mm x Ø 1mm
Distance [m] Data Rate [Gbps] Data Rate x Dist. [Gbps.m] FOM [pJ/bit/m]	0.12 / 1 12.5 / 4.3 1.5 / 4.3 48 / 16.7	0.1 / 1 15 / 10 1.5 / 10 47.3 / 7.1	2 / 7.6 6 / 3.3 12 / 25.1 2.3 / 1.11	0.6 / 9 9 / 2.5 5.4 / 22.5 9.3 / 2.2 (RX only)	1 / 4 / 7 12.7 / 7.4 / 2.5 12.7 / 29.6 / 17.5 4.8 / 1.8 / 4.1
Active area [mm^2]	0.06(TX)+0.14(RX)	0.07(TX)+0.14(RX)	0.06(TX)+0.08(RX)	0.21 (RX only)	0.03(TX)+0.45(RX)
Antenna	Quasi-Yagi on PCB	Quasi-Yagi on PCB	Off-chip dipole	On-chip dipole	On-chip dipole
Modulation technique	ASK	ASK	ASK	Multilevel ASK	CPFSK

Table 1 Performance summary and comparison between state of the art plastic waveguide communication links.

Conclusion:

Based on the combination of three low cost elements: standard CMOS transmitters and receivers, on-chip integrated antennas and low cost plastic polymer fibers, a novel physical layer for Gbps wide-band communication systems is discussed. Compared to copper wireline, the presented solution achieves lower dispersion and higher EMI immunity. Compared to optical interconnects, the presented solution is far more robust against mechanical connector vibrations and the use of on-chip antennas avoids the need of electrical-optical (EO/OE) converters. Other advantages of a plastic waveguide are low cost, low weight and electrical isolation of both connections. Therefore a plastic fiber link is a valuable alternative in automotive, aviation, industrial and consumer applications where Gbps-communication is required.

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